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Interarticulator Timing and Single-Articulator Velocity-Displacement in English Stress Pairs

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Abstract: Models of speech production utilize mentalist accounts of speech phenomena to varying degrees. Especially noted in this paper are accounts of the timing of speech which have sought to eliminate altogether the temporal dimension from mental control. Two major parts of the theory--that in Harris et al. (1986), and that in Kelso et al. (1985)--are explained and tested using a body of X-ray microbeam tracings of articulatory movement in English stress pairs. The first study is a replication of Harris et al. Correlations between jaw movement periods and some variables indicative of the relative timing of lip and tongue-blade movement within the period duplicate those found in Harris et al. However, eliminating the effect of vocalic expandability and the effect of a part-whole relationship between the variables renders the results ineffective in showing the tested timing relationship. The second part replicates Kelso et al. (1985). The present study finds strong correlations between velocity and displacement in jaw movement, both in upward and downward movement, in tokens in normal and frame conditions. In addition, as in Kelso et al., downward movement in stressed syllables shows a shallower regression slope than does downward movement in unstressed syllables. However, in upward movement, the relationship is reversed.

1. Introduction

Much of the work done in linguistics assumes a complex and abstract mental linguistic capability, a mental grammar. Although the actual form of this mental grammar is a matter of heated and continuous debate, the actual existence of some sort of abstract mental linguistic capability is relatively uncontroversial. Anyone interested in understanding what language is at the level of actual production must determine which speech phenomena (or which aspect of a speech phenomenon) are to be seen as indicative of part of this mental grammar, and which are more profitably described in terms of some other set of principles.

Timing is one aspect of speech production which has presented itself as a rather controversial topic in light of this question of the extent of grammatical explanation. The timing of speech events is theoretically cogent to a large range of linguistic notions besides rate, stress, and other prosodic features which come immediately to mind. The treatment of timing in any theory shapes that theory's representation of the segment. Its treatment of timing also impinges upon its account of co-articulation, since the notion "co-articulation" assumes some sort of segment whose production overlaps temporally with neighboring segments.

Approaches to timing have varied considerably in their reliance on mental grammar and their appeal to extra-grammatical principles in explanation. At one extreme are those approaches which treat the timing of articulatory events as almost exclusively the fall-out of mental processes executed upon abstract mental entities. Two examples of such mentalist approaches to handling the temporal overlap of movements associated with adjacent segments--i.e. co-articulation--are those of Wickelgren (1969), and Henke (1966) (explicated in Bell-Berti and Harris 1981, and cf., for a more general discussion of mentalist explanations of speech data, Hammarberg 1976). Wickelgren, for example, assumed a multiplication of mental categories which, in some formal sense, more closely mirror real speech sounds than, say, phonemes would. The result is a detailed, segment-by-segment speech plan which is to be converted into real speech by means of a relatively simple mechanical execution. The actual temporal dimension of such speech plans are often introduced by reference to a mental timing device such as a metronome. The rhythmic pulses generated by such a device are grammatically specified to have some temporal relationship to the various parts of the speech plan. Examples of this type of device are found in Kozhevnikov and Chistovich (1965) and, more recently, MacKay (1985), as well as in Lindblom (1963) and many others.

Non-mental approaches to timing, however, are also attested in the literature. Lindblom's early study of vowel centralization (1963) had a non-mentalist aspect to its mentalist explanation. Vowel centralization was taken to be resultant from articulatory undershoot. Too little time is alloted in unstressed syllables for the tongue body to reach the grammatically specified target for the vowel. Thus, unstressed vowels tend to be centralized. Although this account has not withstood the scrutiny of later study (cf. Gay 1981 and Harris 1978), his methodological insight--that there are articulatory principles which account for co-articulatory phenomena--has found manifestation in other more general theories of speech production, theories which posit a complex and more central physiological component in the study of articulatory timing.

These theories attempt to reduce the role of mental grammar in the explanation of articulatory timing much further than researchers such as Lindblom did. To this end, two differing approaches to timing facts have been taken. An earlier approach (Harris 1978, and Bell-Berti and Harris 1981) involved a linear organization in which the details of production are pre-programmed movements with an internal time dimension which are executed with a fixed temporal overlap with neighboring movements.

The model of speech production examined by this inquiry is a later one presented in Harris, Tuller and Kelso (1986) and various other similar works by these authors. Recently, Kelso et al. (1985) have done work on explicating a crucial aspect of this theory's account of 'timing facts' in speech events. The time specification, it is noted, can be eliminated altogether from the mental input into speech production by modeling the production mechanism as some sort of spring-mass system. During activity, this system undergoes an oscillatory process in which kinetic and potential energy are transferred back and forth. The readily-observable result of this process when mapped over time is a sine wave. (This movement, loosely speaking, is similar to that observed of articulators in real speech.) The temporal dimension then is mathematically dependent on the properties of the spring-mass system--linear stiffness, total mass, etc.--and the perturbing forces acting upon it.

Thus, the clearest evidence cited by Kelso et al. for their approach are strong correlations between the peak velocity of jaw movement and the distance the jaw traverses. Such correlations would be expected within the model, since peak velocity and displacement are both indicative of the energy stored in the spring-mass system. The system in oscillation transfers the energy in one form--potential energy, indicated by displacement from rest position--into energy of the other form--kinetic energy, indicated by peak velocity. Inertia then causes the transfer to be reversed. All three of the variables--peak displacement, peak velocity, and the overall time which the transfer takes (indicated by one quarter of the period of the movement)--are all dependent on the properties of the spring-mass system, as is shown in Figure 1.

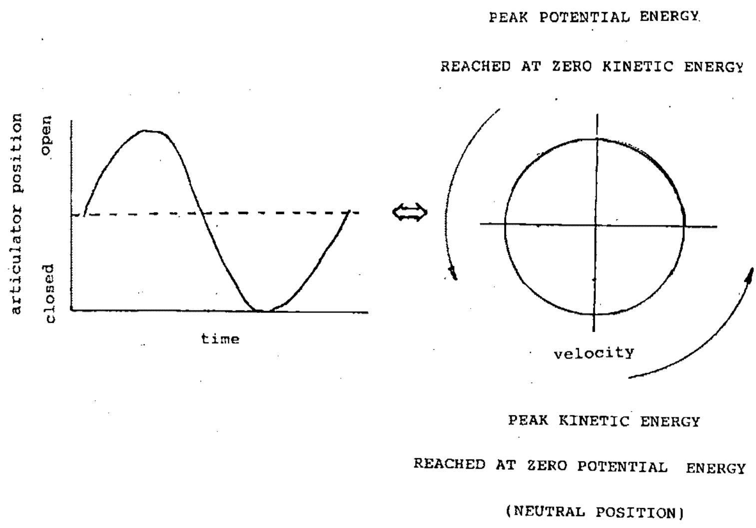

Fig. 1: An illustration of the relationship between a representation of articulatory movement over an explicit time dimension and one utilizing articulator velocity and displacement.

The second part of the theory is explicated in Harris et al. (1986). Normal speech, of course, involves the use of not just one articulator, but many. These articulators have been noted to work co-operatively in the production of various speech segments. For example, in sounds involving a bi-labial stop closure, the jaw and both of the lips co-operate to close off the vocal tract. Due to the immediacy of the co-operation, and the speaker's common unawareness of it, researchers such as Fowler (see especially, Fowler et al. 1980, and as a classic example of the research on which Fowler's position is based, Abbs and Netsell 1973) and others, have positted a low level yoking of the muscles controlling the articulators involved into what is termed a 'co-ordinative structure.'

Harris et al. suggest that the temporal relationship of movements associated with neighboring segments are resultant from the yoking together of muscles (and articulators) at a higher level in a phase relationship. Such phase relationships are exhibited, for example, in the various movements implemented in walking or running. Each of the individual movements comes at a predictable time within the overall stride. If the rate of the stride is increased, rate of each movement within the stride is proportionally increased. Thus, the temporal position of one movement is mathematically predictable from the temporal position of other movements. An illustration of this relationship is given in Figure 2.

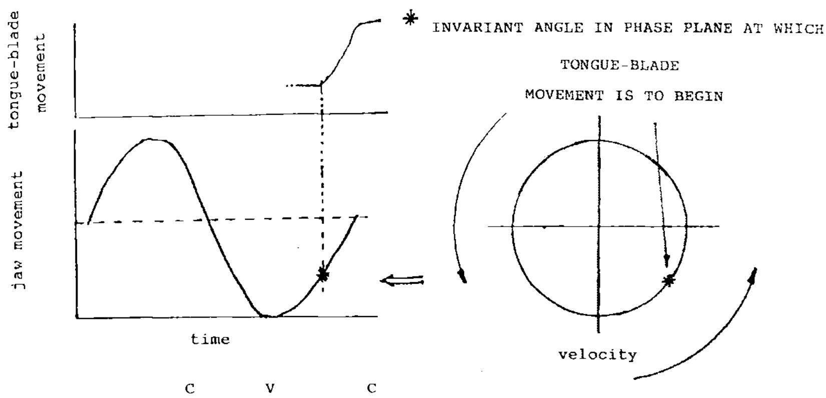

Fig. 2: An illustration of phase plane interarticulatory timing.

The timing of local movement associated with the production of a consonant--shown here as tongue-blade movement--is to occur at an invariant angle in the phase plane portrait depicting the cyclic movement associated with vowels--shown here being indexed by the upward and downward movement of the jaw.

Harris et al. have taken the vowel period to be a global movement similar in kind to the stride in walking. Various other articulator movements come at predictable times relative to this movement. For example, the production of intervocalic consonants is automatically timed in reference to the production of the vowels. The faster the rate of the movement associated with the vowel's production, the faster the rate of the production of the consonants. Thus, to demonstrate this behavior, Harris and others have shown correlations to exist between size of the vowel period--measured as the time between the onset of jaw movement associated with two successive vowels--and the latency of the onset of consonantal (lip or tongue blade) movement from the beginning of the vowel period in the production of various nonsense syllables (e.g. in Harris et al. 1986 and Tuller et al. 1983).

The interpretation of these correlations as evidence for some fixed timing relationship between consonant and vowel production has been criticized on several grounds. Barry (1986) points out several ways in which the correlations could be the artifact of some other fairly well-attested facts. One worrisome criticism has to do with the relative temporal expandability of the vowel, as opposed to the temporal insensitivity of the consonants (cf. Gay 1980). Over variations in rate and stress conditions, a disproportionate share of the temporal expansion or contraction will occur in the vocalic portion of an utterance. Thus, any portion of the vocalic period which is included in both the latency and the period will tend to produce higher correlations between the latency and period.

Another criticism has to do with the interpretation of the obtained correlations in light of a part-whole relationship between the two correlated variables (see Munhall 1986). If one variable is a part of the other variable, a significant correlation between them is expected. A third criticism of these studies points out that both Harris et al. (1986) and Kelso et al. (1985) used a form of non-speech data, either reiterant speech or nonsense words. It is, thus, not clear that their results can be taken as valid for normal speech.

This study will seek to replicate these earlier experiments using real English words of varied stress patterns, placed in two contexts, natural and frame context. It also attempts to take into account the two criticisms noted above. A body of X-ray microbeam data was analyzed. For a replication of Harris et al. (1986), correlations were taken between consonant and vowel periods in jaw movement, and the relative positions of various events in tongue-blade and lip movement. Effort is made to factor out the contribution of vocalic expandability by comparing the predictive power of vowel and consonant periods on the timing of the production of consonants. A second study was also performed, a replication of Kelso et al.'s experiment concerning the relationship between the velocity of jaw movement and the distance it traverses.

2. The Data-base

The data involved in this study consist of the articulatory trajectories of a male speaker of an East Coast dialect of American English. The trajectories were obtained with a computer-controlled X-ray microbeam system at the University of Tokyo. This system utilizes X-ray microbeams which alternately track various metal pellets attached to various articulators during the production of an utterance (see Kiritani et al. 1975 for a more detailed description of this system). The data-base, then, consists of the relative vertical and horizontal (longitudinal) position of each of these pellets--placed on the velum, tongue blade, tongue dorsum, lower lip, mandible, and a reference pellet placed on the nose--after successive time increments. In this study, only three of the pellet traces were used--lip, jaw, and tongue blade.

The analysis of the data-base was performed using the X-ray Database Display Program developed by Joan Miller, implemented on a PC6300 under MS-DOS. This system produces both a one-dimensional display of articulator movement over time (examples of this kind of display are Figures 3 - 5), and a two-dimensional display. The system also includes algorithms for producing velocity functions and combining trajectories in various ways. These algorithms were used to subtract out the contribution of one articulator's movement from that of an other.

The corpus, designed by Mary Beckman, includes eight bi-syllabic English stress pairs involving intervocalic alveolar or palatal consonants. Two pairs involving labial consonants were also studied. Some of the target words occurred in normal English sentences designed to hold the environment of the target as constant as possible; others occurred in the frame sentence, 'Say __________ again.' The targets and sentences are given in Table I. Roughly half of the targets were placed in each context. Most of the natural sentences were repeated twice within each run, while the short frame sentences were repeated from 3 to 5 times in a given run. The number of cases of each pair ranged from 14 to 16. 148 cases were analyzed altogether.

3. Study 1

3. 1. Methods

The temporal distance between the onset of jaw lowering for the first vowel and the onset of movement associated with the second vowel was measured. This measure is taken to be the length of the vowel period. As a matter of comparison, temporal measurements were taken at the zero-velocity point in the negative position

digest (N)	But THIS is how the Reader's Digest talks.
digest (V)	But THIS is how the readers digest talks.
contract (N)	Will you use the older pipe contract as a model for it?
contract (V)	Will even the older pipe contract as much as that?
antics	Their antics are intolerable.
antiques	Their antiques are adorable.
content (N)	You DO know about the content of it.
content (ADJ)	You DO know how to be content about it.
retake (N)	The director wanted a retake the second he saw the developed footage.
retake (V)	The general wanted to retake the second city he had lost.
suspect (N)	The police also think that the FBI-suspect did the crime.
suspect (V)	This is the man that the FBI suspect did the crime.
insight	The poet's insight hurts.
incite	The poets incite hurts.
insult (N)	The soldier's insult counts.
insult (V)	The soldiers insult counts.
deepened	The mountain lakes deepened upon the melting of the winter snow.
depend	The mountain lakes depend upon the melting of the winter snow.
defects (N)	The Russian's major defects and their minor virtues are the same.
defects (V)	The Russian major defects and the corporals under him are punished.

Table I: The corpus.

for the vowels. The difference between these was taken to be indicative of some sort of consonantal period. Example of such marks are shown in Figure 3.

Events in the vertical movement of the tongue blade--or lip, in tokens with labial intervocalic consonants--were also studied. Blade movement was ascertained, as was suggested in Edwards (1985), by finding the difference between the jaw position at a given moment and the mean position of the jaw over the entire utterance. This figure was multiplied by a coefficient reflective of the difference in distance of the jaw pellet and the blade pellet from the jaw hinge--0.8 in the case of the pellet which was attached to the tongue blade. Figure 4 is an example of this spatial relationship. Since the jaw pellet is placed further out on the mandible than the tongue-blade pellet is, it traverses a greater distance for a given swing of the mandible than the tongue-blade. The relationship between the jaw pellet and the lip pellet is, however, the reverse. The lip pellet moves a greater distance than the jaw pellet for a given swing of the jaw. Thus, the coefficient used in subtracting out the jaw's contribution to the observed lip movement is 1.1.

Three events in the movement of the tongue blade were measured--the point at which movement toward the consonant closure began, the point at which that same movement ended, and, finally, the point at which movement began toward the position assumed for the second vowel. Figure 3 is a relatively clear example of the two traces with the appropriate timing marks.

It should be noted that not all of the pairs presented such clearly defined movements. For example, although movement associated with alveolar consonants is usually registered in the movement of the tongue blade, this movement is sometimes obscured by movement associated with neighboring high vowels. The occurrence of /r/, e.g. in **retake**, causes a major upward shift in the movement of the tongue blade. Difficulties are also encountered in radically reduced, unstressed vowels. Often in such words as **depend** and **insult** (V), no vertical jaw-movement is observed during the first vowel. In such unclear cases, the alternative method of display, plotting the vertical and horizontal position of the pellets on an x/y grid,

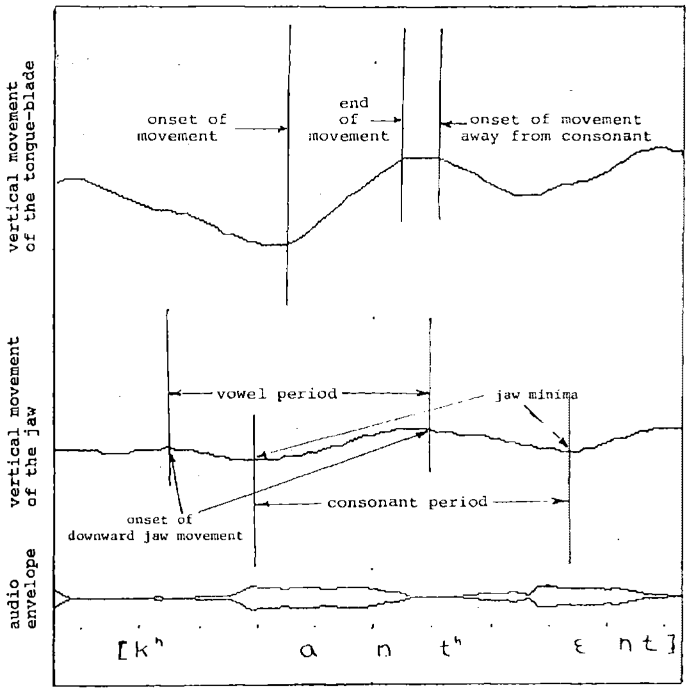

Fig. 3: A tracing of the vertical movement of the tongue blade and jaw during the utterance "Say CONtent again." The timing marks in a latency-period correlation are indicated by vertical lines.

will often reveal subtle changes in the rate and direction of articulatory movement not apparent in the vertical dimension traces. In the few remaining cases, acoustic cues were used, e.g. the alveolar release in **depend** was taken as the beginning of the consonantal period, since there is no jaw-movement associated with the first vowel, as well as no periodic acoustic component.

The reader is referred to Harris et al. (1986) for a short discussion of the validity of these trajectory events as indicators of the events within their model. Unlike that study, only one mark was taken for each case before any of the correlations were calculated.

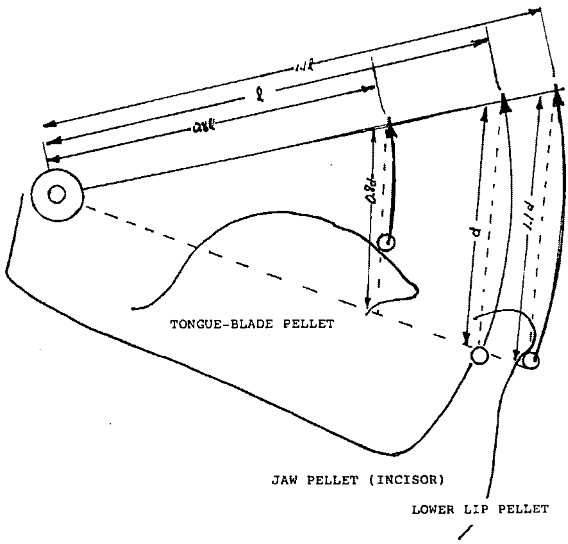

Fig. 4: An abstract depiction of the spatial relationship of the tongue blade and lip pellets to the jaw pellet (see Edwards 1985).

3. 2. Results and discussion

Correlations between latencies calculated with respect to the onset of consonant-articulator movement proved consistently to be the largest of the three events measured as is shown in the figures in Table II. This result, consistent with the findings in Harris et al., suggests that the beginning of the execution of a movement is more salient for the temporal structure of speech than an ending point--target for the consonant--or the onset of tongue-blade or lip movement for the production of the following vowel. These results fit in well with both their contention that articulatory targets are not important in the temporal organization of speech, and that the movement of the smaller articulators--lip and tongue blade, as opposed to jaw--is superimposed over movements associated with the production of the vowels. The differences in r shown here are rather small, but are consistent over the various methods of calculating latencies. The rest of the discussion will, thus, center upon the timing of the onset of movement as opposed to the other two events.

Event	Vowel to Vowel	Consonant to Consonant
Onset of upward movement:	0.7866	0.7031
End of upward movement:	0.6723	0.5924
Beginning of downward movement:	0.6519	0.6792

Table II: Correlations between various events in tongue blade movement and larger periods of movement.

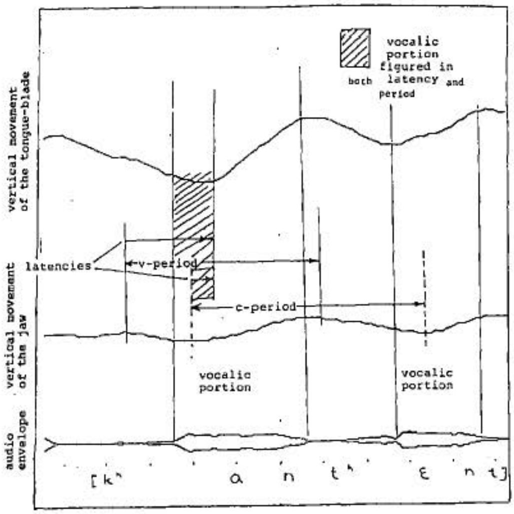

Fig. 5: The amount of the vocalic portion (shaded portion) included in vowel period (upper part) and consonant period (lower part) correlations with the latency of the onset of tongue blade movement.

Correlations were calculated between the latency of the onset of consonant-articulator movement from the beginning of the two periods, and the length of the vowel period and the length of the consonant period as is shown in Figure 5. To investigate the effects of vocalic expandability brought up by Barry, correlations were also calculated between the latency of the end of the periods from the onset of movement associated with the consonant, as is illustrated in Figure 6, and the length of the periods. Correlations are expected to be greater when calculated in the first manner for the vowel period than for the consonant period, since more of the vocalic portion of the utterance is figured into the vowel correlations than into the consonantal correlations. As is shown by the shaded portions of Figure 5, the shaded material in the vowel period latency is larger than that in the consonantal period latencies.

Calculating correlations in the second manner should preserve any indicators of the posited phase relationship, while switching the contribution of the vocalic portion to the vowel period correlation to the consonantal period correlations. In Figure 6, the shaded portion for the consonantal latency is larger than that for the vowel period.

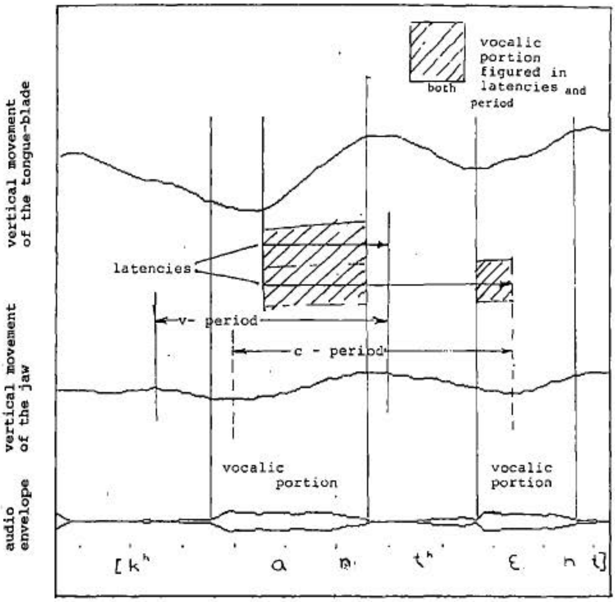

Fig. 6: As in Figure 5. However, the shaded portion indicates the amount of the vocalic portion included when the timing of consonant related movement is ascertained in an alternative method.

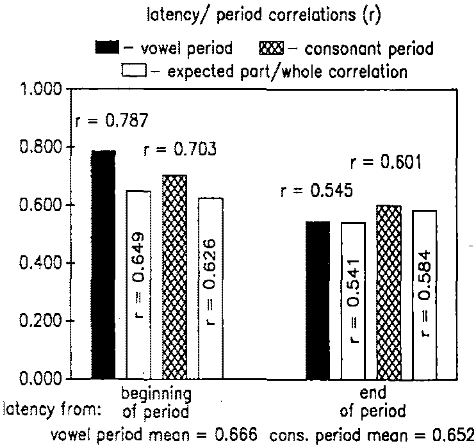

Fig. 7: The regression coefficients for latency-period correlations.

The results taken across all word and stress conditions are shown in Figure 7. The group shown on the left are for the method used in Harris et al. (1986). The group on the right are for an alternative method of ascertaining the relative timing of consonantal movement. Dark boxes are for the vowel period. Light boxes are for the consonantal period. Correlations do exist in the English utterances tested. These results, again, are in keeping with those found in Harris et al., but are slightly weaker. As was pointed out in Munhall (1986) and Barry (1986), significant correlations are expected, since the latency is expected to be some portion of the period. Using the formula in Munhall (1986), expected correlation coefficients were calculated and are also indicated by the open bars in Figure 7.

Considering the relatively unconstrained nature of the corpus, the weaker correlations are not surprising. In order to explain why the correlations for the present corpus were weaker than those found by Harris et. al, some of the differences between the tokens were encoded, either as ordinal variables where possible, or binary dummy variables. Using these variables as second predictors yield the slightly higher correlations in Table III. One variable which, surprisingly, does not yield higher correlations, is the difference between alveolar and labial consonants. This negative result might be considered to be indicative of the internal phase relationship being fixed regardless of the articulator involved. This lack of result might also be attributed to the limited number of labial tokens, and thus, would be expected to disappear with more tokens.

It is apparent from these results that vocalic expandability also plays a part in the correlations. As was expected, larger correlations are found between vowel period and latency than between consonant period and latency. However, when the latencies are calculated in the second manner, the relative size is switched. This pattern is expected, assuming vocalic expandability is the root cause of the difference between the correlations of the two periods. Assuming that the amount of contribution of vocalic expandability to the differences found in the two versions of the calculations are equal, one can neutralize this contribution by taking the mean

Predictors	Vowel to Vowel	Consonant to Consonant
latency X period	0.7866	0.7031
period, stress	0.8007	0.7044
period, articulator	0.7867	0.7034
period, # of cons.	0.7855	

Table III: Latency-Period correlations with multiple predictors.

of the two conditions. The difference between these means is remarkably small, suggesting that the vowel period and the consonant period are equally well-suited to predict the relative temporal position of the onset of tongue-blade movement.

One final result of note here is the large main difference between the correlations figured in the first manner and those figured in the second manner. This difference might be resultant from the figuring of the latencies across the intervocalic syllable boundary. It is a fairly well-attested fact that syllables differing in stress show rather global articulatory and acoustic differences (e.g. Summers 1987). The differences between the two stress-patterns would introduce unaccounted-for variation in the latencies, and, thus, would yield lower correlations. If this is the explanation for the lower correlations, it suggests that both the vowel period and the consonant period might be too-small to account for relative timing of articulatory events across stress conditions. Also lending credence to this approach is the slight effect of adding the stress pattern as a predictor of latency. Of the differences between the types that were encoded, stress is the variable which made the greatest increment in r-squared. Indeed, stress alone correlates significantly with latency, accounting for about 17 percent of the variance in latency ($r = 0.412$).

A direction for future research would be to investigate internal timing relationships in terms of a larger unit of production. It might be more useful, for example, to predict the relative position of the various internal movements within a stress foot by making reference to the overall length of the stress foot. The global unit of production, then, would not be a single cycle of jaw movement, but a more abstract unit of two, or maybe even three cycles. Each cycle would have differing but predictable dynamic properties. For example, trochaic stress feet might consist of a large articulatory cycle, followed by a more restrained cycle. The details of production, according to the phase relationship theory, should then be predictable on the basis of the size of the stress foot.

4. Study 2

4. 1. Methods

The second experiment is an attempt to replicate the velocity-displacement correlations found in Kelso et al. It utilized the same trajectory data-base that was used in the first experiment. Four events in jaw movement were marked and the relative jaw position taken for each event. First, the jaw position at the onset of movement associated with the second vowel as well as the upward position associated with the first medial consonant were marked. The jaw minima associated with each vowel were also taken as is shown in Figure 8. Two displacements were then calculated--downward displacement for the second vowel, and upward displacement for the offset of the first vowel. A velocity function was calculated from the raw vertical trace of jaw movement. Peak upward velocity of the jaw as well as peak downward velocity associated with the production of the medial consonants were then taken.

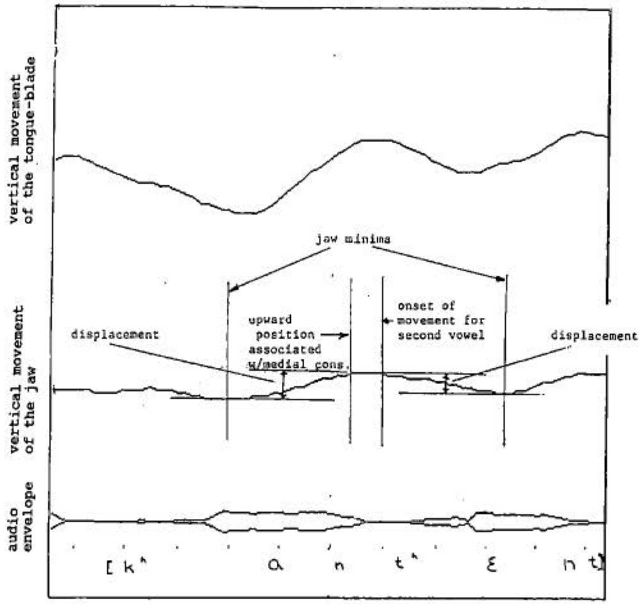

Fig. 8: The same tracings as in Figure 3. Shown here are the (vertical) timing marks and the (horizontal) displacement marks necessary for computing velocity displacement correlations.

4. 2. Results and discussion

Figures 9 - 12 are scatter plots showing every token. As can be seen in these figures, in both the upward movement and the downward movement, and in both natural sentence and frame contexts, peak velocity and amplitude of movement are strongly correlated. These correlations are of the same magnitude as those found in Kelso et al. of reiterant speech. At the outset, I wondered if the correlations might be indicative of a energy-minimizing strategy induced by the repetitive nature of the reiterant speech task. This seems unlikely, since strong correlations are found both in the natural sentences and in often-repeated frame sentences.

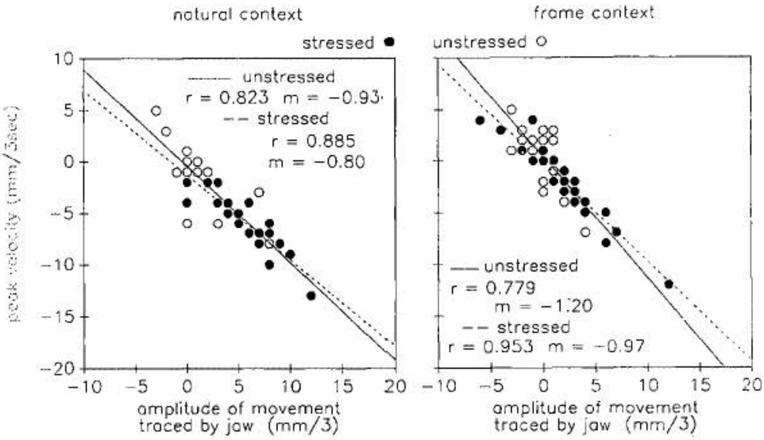

Fig. 9: Scatter plots showing all of the tokens. The velocity (vertical axis) and displacement (horizontal axis) plotted here are for the downward jaw movement into the first vowel of the target words.

One further similarity between the results found here and those in Kelso et al. is shown in Figures 9, 11 and 12. The left graph shows the tokens placed in natural sentences; the right graph shows the tokens placed in an often repeated frame sentence. Solid circles and dashed regression lines indicate movements associated with a stressed syllable, while empty circles and solid regression lines indicate movements associated with unstressed syllables. There is a difference in the slope of the regression lines for stressed and unstressed syllables. Stressed syllables show a shallower regression curve than unstressed. This difference would be indicative of a spring-mass system of less linear stiffness. Thus, a difference noted here between stressed and unstressed syllables is in the rigidity of the articulators, unstressed syllables being marked by a relatively greater resistance to movement. Thus, the jaw traces a period of shorter duration, as well as opening less during unstressed syllables. Both of these features are commonly noted of unstressed syllables--lower amplitude, and shorter duration.

These results, however, are not consistent. Figure 10 shows exactly the opposite patterns in the closing gesture. Stressed syllables show a steeper regression line--indicative of a stiffer spring-mass system. Two explanations for this anomalous result come to mind. One explanation might assume the tensing of the jaw to be an expending of greater effort in the production of the stressed syllable coda. Another explanation would see the difference as a dynamic effect. The tensing of the articulator might be an anticipation of the forthcoming unstressed syllable. Further investigation of slope differences in differing stress and intonational contexts should be able to shed more light on this problem.

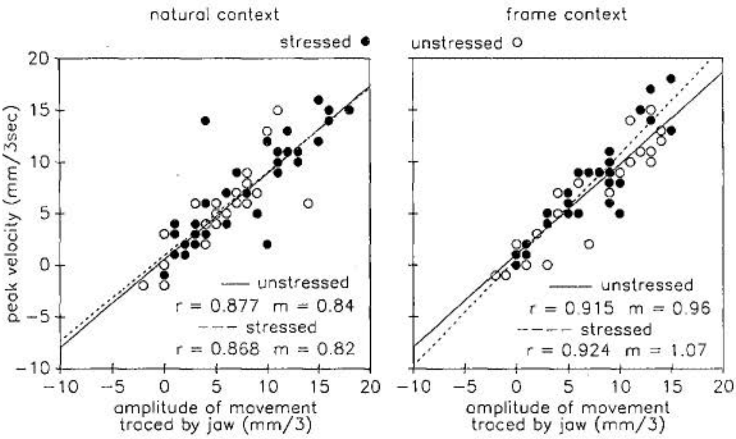

Fig. 10: As in Figure 9. The values plotted here are for the upward jaw movement into the medial consonants in each token.

5. Conclusion

The overall results of the present study duplicate those found in Harris et al. and Kelso et al., suggesting that the models supported in these earlier studies by reiterant speech are extendable to non-reiterant speech and the production of real lexical items. Although there are differences between the data used in this experiment and the natural speech of naive subjects--the presence of metal pellets in the oral cavity, the repetition of well-rehearsed sentences--and although the data is limited to the speech of one speaker, this study is a step toward the application of these models to natural speech.

One of the speakers in Kelso et al. yielded notably smaller velocity-displacement correlations than the other did. Whether this poor correlation is an artifact of the reiterant speech paradigm or indicative of a more general pattern to be found of naive speakers in natural settings is a question for further study. This study shows that the correlation found in the other speaker's production is probably not an artifact of the reiterant speech paradigm.

The velocity-displacement correlations found here are evidence for the validity of the spring-mass model in describing articulatory movement. Its relatively simple account of two of the multiple cues associated with stress--duration and intensity--is rather elegant in that it allows the reduction of the two features to one root cause in languages such as English, where intensity and duration are inextricably connected to stress. But the differing regression slopes found in differing conditions suggest, if the spring-mass model is right, that either there are interactions between neighboring syllables, or that higher level prosodic effects are registered in the stiffness of the spring-mass system.

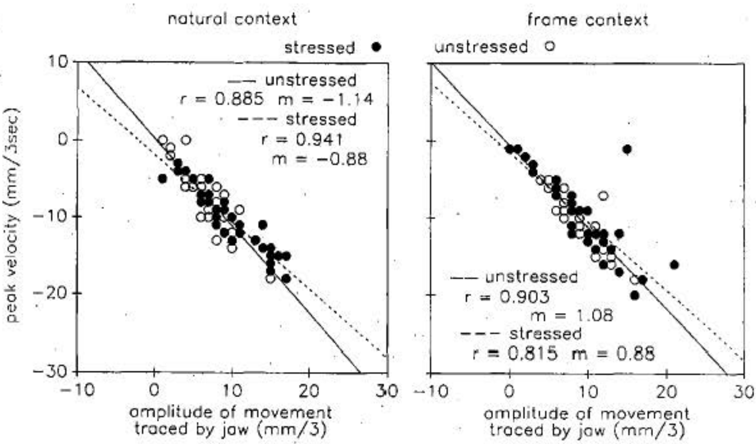

Fig. 11: As in Figure 9. The values plotted here are for the downward jaw movement out of the medial consonants into the second vowel.

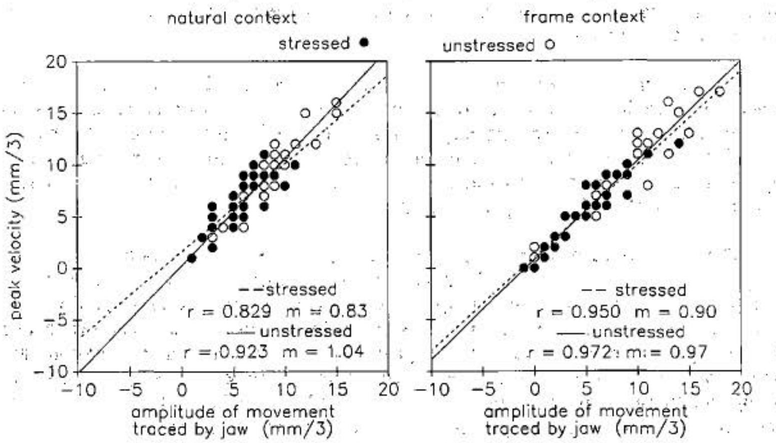

Fig. 12: As in Figure 10. The values plotted here are for the upward movement out of the second vowel.

The interpretation of the results of this study with respect to the posited phase relationship is considerably more difficult. The posited vowel period's importance in the temporal structure of speech does not seem to show any stronger relationship with other movements within the period than a consonant period. Furthermore, temporal organization with respect to the vowel period does not seem to offer any explanation of the rather large difference in correlations obtained by changing the method of calculating the latencies. Beyond these problems, there does not seem to be any ready way of precisely factoring out the relative contribution of vocalic expandability into the observed correlations. This study shows there to be a contribution, but the exact extent of the contribution is unclear.

One final problem has to do with the manner in which the correlations are figured. As long as latencies in each case are a part of the period to which they are correlated, a fairly large correlation can be expected (cf. Munhall 1986). Once vocalic expandability has been factored out, the results here suggest that the significant correlation is a statistical artifact. Given this, there is little in this study to base a claim of a scaled phase relationship in interarticulatory timing, in opposition to other, more traditional, linear theories.

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